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Impact of Ozone on Field-Corn Yield

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16. ABSTRACT
Field corn(Zea mays L.) is the most important agricultural crop in the U.S. and the major production areas are subjected to potentially damaging concentrations of ozone (O_3). Since no information was available regarding the sensitivity of field-corn hybrids grown in the Midwest, plants of two hybrids were field grown in open-top chambers and exposed to O_3 for 83 days to determine its impact on grain yield. The air chamber was either charcoal filtered c non-filtered with various constant amounts of O_3 added to the ambient air from 0[illegible] 1600 CST. Also included was a nonchambered plot. A randomized complete block [illegible] incorporated 3 replicates of 7 treatments. Foliar injury was noted on some p[illegible] the elevated O_3 concentrations but was never more than 5% on an individual le[illegible]alysis of variance of the data indicated significant ozone effects on overall grain yield, 100-seed weight, seeds per cob, cob weight, and cob length, for both hybrids. Small reductions in overall yield were due to reduced individual seed weight. Larger overall yield reductions were due to reductions in seed weight and number. Three nonlinear models were tested to describe the responses of the hybrids to O_3 & the models were not statistically different from each other. A comparison of the open plots with the nonfiltered air-chamber plots provided with the same O_3 concentration revealed no significant chamber effects for any of the seed yield parameters.

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Impact of ozone on field-corn yield[1]

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KRESS, L. W., and J. E. MILLER. 1985. Impact of ozone on field-corn yield. Can. J. Bot. **63**: 2408–2415.

Field corn (*Zea mays* L.) is the most important agricultural crop in the United States, and the major production areas are subjected to potentially damaging concentrations of ozone (O_3). Since no information was available regarding the sensitivity of field-corn hybrids grown in the Midwest, plants of two hybrids ('Pioneer 3780' and 'PAG 397') were field grown in open-top chambers and exposed to O_3 (7 h/day seasonal means of 0.015, 0.044, 0.073, 0.100, 0.129, and 0.156 ppm) for 83 days to determine the impact of O_3 on grain yield. The air in the chambers was either charcoal filtered or nonfiltered with various constant amounts of O_3 added to the ambient air (mean of 0.044 ppm) from 0900 to 1600 Central Standard Time. Also included was a nonchambered plot. A randomized complete block design incorporated three replicates of seven treatments. Foliar injury was noted on some plants at the elevated O_3 concentrations but was never more than 5% on an individual leaf. Analysis of variance of the data indicated significant ozone effects on overall grain yield, 100-seed weight, seeds per cob, cob weight, and cob length, for both hybrids. Small reductions in overall yield were due to reduced individual seed weight. Larger overall yield reductions were due to reductions in seed weight and number. Three nonlinear models were tested to describe the responses of the hybrids to O_3 and the models were not statistically different from each other. The Weibull survival function was used to test for heterogeneity of hybrid responses, and the responses were found homogeneous. The Weibull model predicted yield losses of 2.6% at 0.06 ppm and 16.3% at 0.10 ppm relative to 0.025 ppm O_3. A comparison of the open plots with the nonfiltered air-chamber plots provided with the same O_3 concentration revealed no significant chamber effects for any of the seed yield parameters.

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Le maïs (*Zea mays* L.) est la culture la plus importante aux États-Unis, et la majeure partie des surfaces cultivées sont soumises à des concentrations potentiellement dommageables d'ozone (O_3). Aucune donnée n'étant disponible sur la sensibilité à l'ozone du maïs hybride cultivé dans le Midwest, des plantes de deux hybrides ('Pioneer 3780' et 'PAG 397') furent cultivées au champ en chambres à toit ouvert et exposées à l'ozone (7 h/jour avec une moyenne saisonnière de 0,015, 0,044, 0,073, 0,100, 0,129 et 0,156 ppm) durant 83 jours en vue de déterminer l'impact de l'ozone sur le rendement en grains. L'air des chambres a été soit filtré sur charbon ou soit non-filtré. Diverses quantités d'ozone furent ajoutées à l'air ambiant (moyenne de 0,044 ppm) à partir de 0900–1660 Heure normale centrale. De plus, une parcelle n'étant pas une chambre fut incluse dans l'expérience. Le dispositif expérimental était un bloc complet au hasard incorporant trois répétitions de sept traitements. Les dommages au feuillage furent observés chez certaines plantes aux concentrations élevées en ozone mais n'ont jamais dépassé 5% sur les feuilles individuelles. Des résultats significatifs furent obtenus pour le rendement total en grains, le poids de 100 grains, le nombre de grains par épi, le poids des épis et leur longueur pour les deux hybrides. De faibles réductions du rendement total sont dues à la diminution du poids des grains individuels. Les réductions plus importantes de rendement sont dues à la baisse du poids et du nombre des grains. Suite à des tests d'hétérogénéité, les réponses des hybrides à l'ozone ont été jugées homogènes. Le modèle de Weibull a prédit des pertes de rendement de 2,6% à 0,06 ppm et de 16,3% à 0,10 ppm relativement au traitement avec 0,025 ppm d'ozone. La comparaison des parcelles ouvertes avec celles des chambres dont l'air n'avait pas été filtré et ayant reçu les mêmes concentrations d'ozone n'a pas révélé d'effets de chambre significatifs pour aucun des paramètres de rendement des semences.

[Traduit par le journal]

Research and field observations suggest that ozone (O_3) may be responsible for up to 90% of the crop loss in the United States caused by air pollution (Heagle and Heck 1980; Heck *et al.* 1982; Lokey *et al.* 1979). The available air quality monitoring data suggest that elevated O_3 concentrations occur in much of the Midwest and parts of the eastern and southeastern United States where field corn (*Zea mays* L.) is of major importance (Reagan 1982; Clark 1980; Anonymous 1978). Mean growing season O_3 concentrations ranging from 0.05 to 0.07 ppm (seasonal 7 h/day mean, 0900–1600 Standard Time (ST)) occur over most of these regions. A growing-season mean concentration of 0.06 ppm O_3 has been estimated to reduce the yields of crops such as soybean (18.8%), wheat (3.6%), and cotton (15.2%) (Heck *et al.* 1983); however, field corn appears to be relatively insensitive (Heagle and Heck 1980; Miller *et al.* 1982). Heagle, Philbeck, and Knott (1979) have reported the only field-generated dose–response information for field corn. They exposed hybrid 'Coker 16' to four O_3 concentrations (0.02, 0.07, 0.11, 0.15 ppm) in open-top chambers and found a significant (ANOVA) grain yield reduction only for the 0.15 ppm O_3 treated plants. Weibull regression analysis of the same data predicted losses of 0.3% at 0.06 ppm O_3 and 2.9% at 0.10 ppm O_3 relative to yield at 0.025 ppm (Heck *et al.* 1983).

Despite the apparent insensitivity of field corn to O_3, it was deemed necessary to study further the response of field corn to a range of O_3 doses. The reasons for this included that (*i*) field corn is the most important crop economically and even a small yield effect could have a large economic impact; (*ii*) it is of greatest importance in the United States Midwest and the sensitivity had not been evaluated in that region; (*iii*) only one hybrid has been examined previously; and (*iv*) the previous study did not include enough O_3 concentrations to describe the

[1]Although the research described in this article has been funded (wholly or in part) by the United States Environmental Protection Agency through contract No. AD-89-F2544 to Argonne National Laboratory, it has not been subjected to the agency's required peer and policy review and therefore does not necessarily reflect the views of the agency and no official endorsement should be inferred.

dose–response function adequately.

The study reported herein reflects a portion of the research conducted at Argonne National Laboratory (Argonne, IL) as a member of the National Crop Loss Assessment Network (NCLAN) in 1981. Most of the methods and procedures of exposing plants to air pollution have been standardized among the cooperating scientists (Heck *et al.* 1982; Heck *et al.* 1983). The specific objective of this study was to determine the impact of ambient O_3 and four O_3 concentrations above ambient on the grain yield of two commercial hybrids of field corn that are commonly grown in the United States corn belt.

Materials and methods

The site of this research is located approximately 40 km southwest of Chicago, IL, at Argonne National Laboratory. The research plot was used for soybean production in 1980 and had been in undisturbed turf for at least 20 years prior to that. The soil is a Morley silt loam (fine, illitic, mesic Typic Hapludalf), upland timber soil. This soil has a high water-holding capacity, low permeability, a pH of 6.6 ± 0.6, and 59 360 ± 5 600 kg/ha organic matter. Soil test results following the 1980 season indicated 21 ± 7 kg/ha P, and 180 ± 30 kg/ha K. The experimental plot (0.3 ha) was plowed, fertilized with 672 kg/ha of 9–23–30 and 355 kg/ha of urea (160 kg N/ha), and then disced several times in April and May 1981. Soil tests following the 1981 field season indicated 28 ± 13 kg/ha P and 218 ± 34 kg/ha K.

Two commonly planted commercial hybrids of field corn (*Zea mays* L. 'Pioneer 3780' and 'PAG 397') were planted on 28 May 1981, utilizing a 76-cm row spacing and a 17.8-cm plant spacing in each row (73 900 plants/ha). Experimental plots (46) incorporated two rows of each hybrid planted next to each other so that the east two rows were 'Pioneer 3780' and the west two rows were 'PAG 397'. The centre two rows (one row of each hybrid) each had 16 plants, the middle 12 of which were to be evaluated. The remainder of the plants, both inside and outside of the plots, were grown to provide competition and adequate pollen. Throughout the season the plots were hand weeded when necessary. Seasonal rainfall was above normal (May, 9.36 cm; June, 15.37 cm; July, 10.31 cm; August, 17.88 cm) and no artificial irrigation was applied. No pesticides were applied because only sporadic minor infestations of aphids and sooty mold developed late in the season on the lower leaves.

Open-top chambers 3 m diam by 2.43 m high, as described by Heagle *et al.* (1973), Heagle, Philbeck, and Knott (1979), and Heck *et al.* (1982), were established over 20 experimental plots on 19 June, and O_3 treatments took place from 20 June to 10 September 1981. The exposures began when the corn plants were about 15 cm tall (16 days from germination) and were terminated when the kernels had ceased filling (as indicated by dent formation and development of the black layer in the kernels).

The experiment consisted of a randomized block design incorporating three replicates (blocks) each of seven treatments. The treatments were AA, no chamber; CF, charcoal-filtered air chamber; NF-1, nonfiltered air chamber with a small amount of O_3 added to provide a concentration equal to that in ambient air (a small amount of O_3 is lost as the ambient air passes through the particle filter, fan, and chamber assemblies); and NF-2, NF-3, NF-4, and NF-5, nonfiltered air plus approximately 0.03, 0.06, 0.09, and 0.12 ppm O_3 above ambient levels, respectively. These treatments thus encompassed a wide range of conditions ranging from relatively O_3 free to highly O_3 polluted. In addition, there was an extra NF-1 treatment in two of the blocks and there were 23 extra AA plots distributed uniformly over the study area to estimate field variability.

Ozone was added to the chambers from 0900 to 1600 CST daily, since the plants are most active metabolically and O_3 concentrations are usually highest during that time period. The chamber fans were turned off nightly (2130–0530) to allow dew formation and to reduce the chamber effect on yield. Since O_3 concentrations are generally low during extended rainy periods, fumigations were not made then. Decisions were made twice daily (0900 and 1230 CST) whether or not to initiate the O_3 addition treatments. The combination of rain and completely overcast skies dictated that the O_3 treatments not be started. Of 83 possible fumigation days, exposures on 3 full days and 4 half-days were cancelled because of rain (but the O_3 concentrations were still recorded and included in the seasonal means).

Ozone generation and monitoring have been described in detail previously (Heagle, Philbeck, Rogers *et al.* 1979; Kress and Miller 1983). All O_3 sampling lines were of uniform length and their efficiencies in transmitting O_3 were checked prior to, during, and following the experiment. Sampling line losses of 7–8% were noted and concentration measures were corrected. Bendix[2] chemiluminescent O_3 monitors (Combustion Engineering, Lewisburg, WV) were calibrated with a Columbia Scientific Industries Photocal 3000 (Columbia Scientific Industries, Austin, TX) several times per week, and an independent audit during the experiment verified correct instrument operation. Two O_3 monitors each sampled 10 chambers and 1 open plot on a 2 min/plot time share system. Thus, each chamber and two open plots were sampled for 2 out of every 22 min (only the last minute of each reading was used in concentration calculations). All O_3 sampling inlets were at canopy height early in the season and at ear height (0.9 to 1.3 m) from midseason on. A third monitor sampled ambient O_3 continuously at a 6-m height.

All plants were evaluated for pollen dehiscence, style development, number of leaves, and plant height on 30 July. Foliar injury was evaluated on the ear leaf on 5 September. The ears were harvested on 5 October and total height and height to the ear were measured on 6 October. The center two rows in each plot (one row of each hybrid) contained 16 plants per row and the middle 12 plants (2.14 m) were sampled in four groups of three (for a within-chamber sample variation estimate). Cob length and the length of cob with kernels were measured. The grain was separated from the cobs, and then both were oven-dried at 64°C to <1% moisture content. Grain and cob samples were weighed and 100-seed weights were also taken for each sample. The number of seeds per cob was calculated by dividing the seed weight per cob by the 100-seed weight and multiplying by 100. Soil samples were collected from each of the 46 plots after plant harvest. Five 10 in. (1 in. = 25.4 mm) deep cores were pooled from each plot. Analyses for pH, organic matter (OM), P, and K were performed by the Soil and Plant Analysis Laboratory, University of Wisconsin–Extension.

An analysis of covariance for chambered plot yield (kilograms dry grain per hectare) using the average yield of the four ambient plots surrounding each chambered plot as the covariate indicated no significant effect of the covariate. For further analyses, if the AA plots were included, two randomly selected (prior to the experiment) AA plots per block were utilized. To determine if there were any significant position effects within the chambers, an analysis of variance (ANOVA) was performed using the four three-plant subsamples per hybrid per plot, using only the chambered plot data.

An analysis of variance was performed for each hybrid separately (with and without the nonchambered plot data) to determine ozone (treatment) and block (replication) effects on overall grain yield (kilograms per hectare), 100-seed weight, seeds per cob, cob weight, cob length, percent of the cob with kernels, plant height, and height to the ear. The initial statistical analyses were performed on an imbalanced data set (five plots for NF-1 and three plots each for the other chamber treatments). Linear models and nonlinear models handled the imbalance in different ways, and this created a problem in comparing the models and estimating their adequacy. Therefore, for the purpose of model testing, a balanced data set was created by averaging the two replications of the NF-1 treatment in each of two blocks. A split-plot analysis of variance was performed (with and without the nonchambered plot data) to determine ozone, block, and hybrid effects on grain yield (kilograms per hectare). Regression equations were developed

[2]Any mention of a trademark or proprietary product does not imply approval or recommendation of these products by Argonne National Laboratory or sponsors, to the exclusion of other products that may be suitable.

TABLE 1. Hourly average ambient O_3 concentrations (parts per million) that are exceeded for various percentages of particular monitoring periods from 1 June to 30 September 1981

Time frame	No. of measurements	% of time concentration is exceeded								
		Minimum	90	70	50	30	10	5	1	Maximum
0900–1600	854	0.003	0.019	0.032	0.042	0.051	0.068	0.077	0.094	0.116
0500–2000	1830	0.000	0.007	0.021	0.032	0.044	0.062	0.072	0.085	0.122
0000–2400	2928	0.000	0.002	0.013	0.024	0.036	0.055	0.066	0.084	0.122

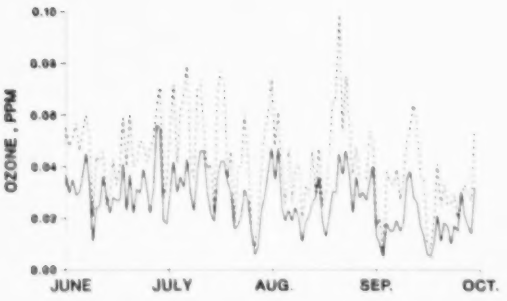

FIG. 1. Ambient ozone data collected from 1 June to 30 September 1981, showing daily 7-h mean (0900–1600 CST) (---) and daily 24-h mean (—). Experimental treatments ran from 20 June to 10 September.

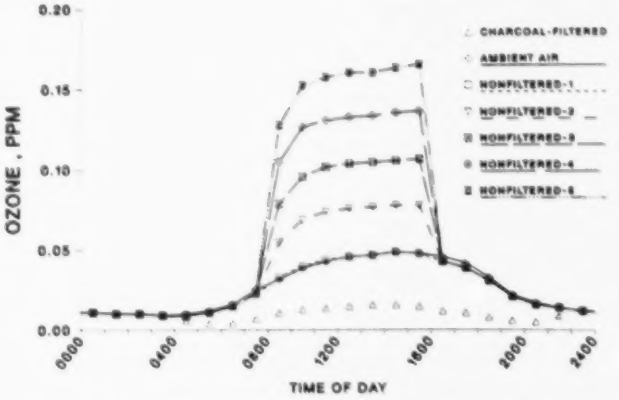

FIG. 2. Diurnal pattern of mean hourly ozone concentrations in ambient air (AA), charcoal-filtered air chambers (CF), or in nonfiltered chambers with various amounts of O_3 added from 0900–1600 CST 20 June to 10 September 1981. The 7 h/day seasonal average mean parts per million for each treatment was as follows: CF, 0.015; AA, 0.044; NF-1, 0.044; NF-2, 0.073; NF-3, 0.100; NF-4, 0.129; NF-5, 0.156 ppm. All chamber fans were turned off nightly from 2130 to 0530 CST.

for grain yield (kilograms per hectare) as a function of O_3 concentration (chambered plots only). Linear and quadratic models were produced utilizing the SAS[1] general linear models (GLM) procedure and plateau–linear and Weibull models were produced by the SAS nonlinear procedure (PROC NLIN) (Anonymous 1982). The Weibull model, $y = \alpha e(-(x/\sigma)^c)$, which we will call the relative crop performance or dose response function for a pollutant, was previously chosen for use by NCLAN from among several reasonable nonlinear models because of its form and flexibility (Heck *et al.* 1983). The parameter σ is the dose at which relative performance has been reduced to e^{-1} (= 0.368). The parameter c controls the shape of the performance curve; $c = 1.0$ gives the familiar exponential decay curve and larger values of c reduce the impact of low doses and increase the rate of response as the σ value is approached, giving the appearance of a dose threshold. To predict the actual crop yield at various O_3 concentrations, the exponential part of the model $(e(-(x/\sigma)^c))$ is multiplied by α, the yield at 0.00 ppm O_3. The homogeneity of the responses to O_3 of the two hybrids was tested by partitioning the (ozone + hybrid) sum of squares (SS) into three types of Weibull models (Rawlings and Cure 1985). The "simple" Weibull requires the same yield level and response to O_3 for both hybrids. The "common" Weibull allows different yield levels for the hybrids but requires the same proportional response to O_3. The "full" Weibull allows each hybrid to have its own yield level and response to O_3.

Results

Ozone concentrations

Since the O_3 exposures are not fully described by the 7 h/day seasonal mean statistic alone, the O_3 concentrations have been expressed in several ways that allow a more detailed evaluation of the exposure regimes. Concentrations of O_3 in ambient air from June through September of 1981 are summarized as daily 7- (0900–1600 CST) and 24-h means (Fig. 1). The highest ambient 7-h mean was 0.099 ppm on 21 August and the highest 24-h mean was 0.056 ppm on 28 June. The 7-h mean was usually considerably greater than the 24-h mean, as would be expected from the diurnal pattern of O_3 concentrations. The ambient O_3 data were also described by listing ambient concentrations that are exceeded for various percentages of time during the specified monitoring periods (Table 1). This table helps provide an indication of the relationship between high and low hourly O_3 values and the diurnal variation in O_3 concentrations.

The diurnal pattern of the mean hourly O_3 concentrations for the seven experimental treatments is presented in Fig. 2. While the curves are smooth, because they are mean values, the concentrations actually varied in intensity from day to day, depending upon the ambient O_3 concentration as in Fig. 1. The O_3 in the CF treatments was observed to decrease below ambient while the chamber fans were operating, and all treatments generally tracked the ambient pattern during the 7-h exposure period. The highest and second highest hourly and 7-h values and the seasonal 1-h peak and 7-h means (Table 2) provide information regarding the relationship between high and low O_3 concentrations for each treatment (e.g., peak to mean ratios). The U.S. Environmental Protection Agency national ambient air quality standard (NAAQS) for O_3 (0.12 ppm hourly average not to be exceeded more than once per year) was not violated in the ambient air, CF, or NF-1 treatments, but it was violated in all the above ambient treatments (NF-2 through NF-5).

Plant development and foliar injury

While the total rainfall for each month of the growing season was above normal, there were some periodic signs of moisture stress (leaf curling), especially early in the season, from which

[1]SAS is a registered trademark of SAS Institute, Inc., Cary, NC.

TABLE 2. Highest and second highest hourly (within the 0900–1600 CST time frame) and 7-h mean O_3 values, the seasonal 1-h daily peak mean, and the seasonal 7-h (0900–1600 CST) mean for each treatment, 20 June – 10 September 1981

Treatment	Hourly concn. (ppm)			7-h concn. (ppm)		
	Highest	Second highest	Seasonal peak mean	Highest	Second highest	Seasonal mean
Ambient	0.116 (0.122)[a]	0.114	0.055	0.099	0.077	0.044
CF	0.065	0.064	0.018 (0.024)[b]	0.056	0.031	0.015
NF-1	0.118	0.116	0.053	0.099	0.077	0.044
NF-2	0.154	0.148	0.084	0.135	0.114	0.073
NF-3	0.188	0.184	0.116	0.166	0.152	0.100
NF-4	0.221	0.216	0.148	0.199	0.184	0.129
NF-5	0.248	0.247	0.178	0.223	0.208	0.156

[a] Highest hourly value occurred outside the 0900–1600 time frame.
[b] The daily highest hourly value in CF treatments occasionally occurred at night while the fans were off. Value in parentheses is for entire 24-h period.

TABLE 3. Significance of block and ozone effects for two field-corn hybrids exposed to 7-h seasonal means of 0.015, 0.044, 0.073, 0.100, 0.129, or 0.156 ppm O_3 for 83 days during 1981, using only chambered plot data

Source[a]	df	Grain yield (kg/ha)	100-seed weight	Seeds per cob	Cob weight	Cob length	% cob length with kernels	Plant height	Height to ear
				'Pioneer 3780'					
Blocks	2	418 925	2.422	1 451.99	12.589	0.546	12.876	0.215**	0.0185*
Ozone	5	24 552 113 **	56.816**	20 168.82**	365.578**	11.877**	18.057	0.0048	0.0056
Residual	(15) 17	(585 188)	1.086	2 512.34	19.536	0.5846	8.196	0.0033	0.0037
Coefficient of variation		6.86	3.97	9.49	7.82	3.43	3.81	2.27	6.02
				'PAG 397'					
Blocks	2	8 892 486 **	2.386	14 984.19*	122.854	1.379*	61.835*	0.0283**	0.0156
Ozone	5	24 717 296 **	61.921**	15 802.63**	818.536**	17.327**	28.005	0.0386**	0.0365**
Residual	(15) 17	(1 058 294)	1.762	2 456.02	21.672	0.196	10.013	0.0034	0.0043
Coefficient of variation		8.67	5.38	9.96	6.26	2.01	3.37	2.68	6.04

NOTE: *, **, significant at the 0.05 and 0.01 level, respectively.
[a] ANOVA performed on balanced data set for kilograms per hectare but on complete unbalanced data set for all other parameters. (Data were balanced by averaging the two NF-1 plots in each of two blocks. Residual is from ANOVA including nonchambered plots to capitalize on additional degrees of freedom.)

the plants recovered with no obvious lasting effects. The plant evaluations on 30 July revealed no treatment differences for pollen dehiscence, style development, number of leaves, or plant height. There were some apparent hybrid differences in that 'PAG 397' was taller and 'Pioneer 3780' shed pollen and displayed style about 5 days earlier than 'PAG 397'.

Foliar injury on both hybrids was noted in early September in the 0.100 ppm, 0.129 ppm, and 0.156 ppm O_3 treated plots. Necrotic interveinal flecking, necrotic tips, and mild chlorotic interveinal streaking (similar to magnesium deficiency) symptoms increased above 0.073 ppm, but even in the most severe treatment the injury amounted to less than 1% necrosis and 5% chlorosis on individual leaves.

Plant growth and yield effects

An analysis of variance of the 26 ambient plots (AA) revealed no pattern of variation in overall grain yield across the field. The blocking of the three replications appeared to be as effective in accounting for environmental variation as using the ambient plot yield values as covariates in a covariance analysis. An analysis of variance of the soil factors (pH, OM, P, K) from both chambered and nonchambered plots also showed no significant variation across the field and no treatment by soil factor interactions.

The test of within-chamber position effects indicated no position effect on grain yield of either 'Pioneer 3780' or 'PAG 397'. No significant ozone treatment by position interactions were found for either hybrid. There was an apparent chamber effect for plant height in both hybrids but not for the seed weight variables.

The analysis of variance test of plot averages indicated highly significant ozone effects on grain yield (kilograms per hectare), 100-seed weight, seeds per cob, cob weight, and cob length for both hybrids (Table 3). Highly significant ozone effects were also noted for 'PAG 397' in plant height and height to ear. Significant block effects were noted for several of the plant growth variables but more commonly for 'PAG 397'. The occurrence of significant block effects indicated that our blocking design was effective in explaining a significant amount of our total variation and removed that variation from the estimate of experimental error

The yield and plant growth data indicated little effect of O_3 until the concentration exceeded 0.073 ppm for 'Pioneer 3780' and 0.100 ppm for 'PAG 397' (Table 4). Once this apparent "threshold" was exceeded, grain yield was drastically reduced as O_3 was increased. Individual seed weight (100-seed weight)

TABLE 4. Yield and growth responses of two field-corn hybrids exposed to charcoal-filtered air (CF), ambient air open plot (AA), and ambient air plus O_3 in open-top chambers for 83 days during 1981

		'Pioneer 3780'							'PAG 397'						
Treatment[a]	7-h mean O_3 (ppm)	Grain yield (kg/ha)[b]	100-seed weight (g)	Seeds per cob	Cob weight (g)	Cob length (cm)	% cob length with kernels	Plant height (m)	Height to ear (m)	Grain yield (kg/ha)[b]	100-seed weight (g)	Seeds per cob	Cob weight (g)	Cob length (cm)	% cob length with kernels	Plant height (m)	Height to ear (m)
AA	0.044	10 675	23.9	533	58.8	20.9	90.8	2.13	0.88	12 190	24.3	594	78.8	22.5	93.2	2.37	1.11
		(97)[c]	(93)	(105)	(96)	(103)	(103)	(93)	(90)	(103)	(95)	(108)	(101)	(100)	(104)	(93)	(87)
CF	0.015	10 991	25.7	509	61.5	20.2	88.3	2.29	0.98	11 832	25.8	549	78.4	22.4	89.8	2.55	1.28
NF-1	0.044	10 743	24.3	526	59.4	20.7	87.4	2.28*	0.97	12 911	26.6	578	82.6	22.9	93.0	2.53*	1.23*
		(98)	(95)	(103)	(97)	(102)	(99)	(100)	(99)	(113)	(103)	(105)	(105)	(102)	(104)	(99)	(96)
NF-2	0.073	10 909	24.7	527	62.0	20.9	88.2	2.30	1.01	11 461	25.3	538	75.8	22.3	89.4	2.47	1.14
		(99)	(96)	(104)	(101)	(103)	(100)	(100)	(103)	(97)	(98)	(98)	(97)	(100)	(100)	(97)	(89)
NF-3	0.100	8 237	20.0	491	54.2	19.8	87.5	2.30	0.97	11 044	24.0	548	70.6	22.2	91.0	2.53	1.26
		(75)	(78)	(96)	(88)	(96)	(99)	(100)	(99)	(93)	(93)	(100)	(90)	(99)	(101)	(99)	(98)
NF-4	0.129	6 101	17.6	417	46.2	17.9	88.5	2.25	0.92	8 319	18.6	531	59.9	20.2	89.0	2.45	1.17
		(56)	(68)	(82)	(75)	(89)	(100)	(98)	(94)	(70)	(72)	(97)	(76)	(90)	(99)	(96)	(91)
NF-5	0.156	4 231	15.4	326	34.3	15.9	82.1	2.20	0.89	5 040	15.9	379	39.4	16.7	84.2	2.25	0.98
		(38)	(60)	(64)	(56)	(79)	(93)	(96)	(91)	(43)	(62)	(69)	(50)	(75)	(94)	(88)	(77)

NOTE: *, significantly different ($P = 0.05$) from the AA plot according to the Duncan's new multiple-range test; only NF-1 was tested for differences with AA plot.
[a]AA, each value derived from 72 plants (6 plots); NF-1, each value derived from 60 plants (5 plots); all others, each value derived from 36 plants (3 plots).
[b]Kilograms per hectare yields adjusted to reflect 15.5% moisture content (62.5 kg/ha = 1 bu/acre).
[c]All numbers in parentheses are derived values expressed as percentage of CF plot.

appeared to be responsible for most of the reductions in overall grain yield at 0.100 ppm for 'Pioneer 3780' and 0.129 ppm for 'PAG 397'. As the O_3 concentrations increased, the number of seeds per cob decreased and contributed to an even more rapid decrease in overall grain yield. At the highest O_3 concentration (0.156 ppm) the percent of the cob that was filled with kernels also began to show some reduction, and reductions in seed weight and number appeared to be equally responsible for overall grain yield reduction. The reductions in individual seed weight were accompanied by fairly comparable reductions in cob weight and the reductions in seed number were similar to the reductions in cob length.

Exposure–response models

The linear models did not adequately describe the response of either corn hybrid to O_3 as indicated by the lack-of-fit (lof) tests (Table 5). The lof tests performed on the nonlinear models indicated that all models provided adequate fits, and the R^2 determinations showed virtually no differences among them. However, the predicted yields did differ somewhat among the models (Table 6), but the greatest difference was only 6.6% at the 0.073 ppm data point for hybrid 'Pioneer 3780'. For all other data points for both hybrids the differences were less than 5%.

The Weibull model was used to develop a combination model to test for homogeneity of the hybrid responses to O_3. The split-plot analysis indicated highly significant ozone, block, and hybrid effects for overall grain yield (Table 7). The lack of significance for the "hybrid × ozone" term indicated that the two hybrids were homogeneous in their response to O_3 (on an additive scale), and the significant "hybrid" effect was due to differences in absolute yield. The simple Weibull model (includes a single α, σ, and c parameter for both hybrids combined) accounted for 89% of the (ozone + hybrid) variation for kilograms per hectare yield. The common Weibull model (separate α for each hybrid but a common σ and c parameter) accounted for 97% of the variation and was a significant improvement over the simple Weibull. The full Weibull model (separate α, σ, and c for each hybrid) was not a significant improvement over the common Weibull, providing further indication that the proportional responses to O_3 of the two hybrids are homogeneous. The lof tests were not significant, indicating that the models adequately described the responses. The parameters for the common model are presented in Table 7.

The regression curves (Weibull and quadratic for 'PAG 397' and Weibull and plateau–linear for 'Pioneer 3780') for yield as a function of O_3 concentration are shown in Fig. 3. The individual plot data points indicate little response to O_3 below about 0.07 ppm for 'Pioneer 3780' and about 0.10 ppm for 'PAG 397'. The quadratic model fit for 'PAG 397' did describe the slight increase in yield at the ambient O_3 concentration (the Weibull model does not allow for a yield increase) but continued to predict a yield increase at 0.073 ppm O_3. Above 0.073 ppm O_3, the two models were nearly identical. The plateau–linear model for 'Pioneer 3780' came closest to fitting the 0.073 ppm data point by estimating a threshold concentration of 0.071 ppm, below which the model assumes no O_3 effects.

Discussion

Field corn appears to be relatively tolerant to O_3 at low to moderate concentrations (0.015–0.07 ppm as 7-h means).

TABLE 5. Models developed to describe overall grain yield response of two field-corn hybrids exposed to O_3 in open-top field chambers for 83 days in 1981

Model[a]	df	'Pioneer 3780' SS	MS	F	R^2	'PAG 397' SS	MS	F	R^2
Linear	1	107 832 614	107 832 614		0.88	95 489 774	95 489 744		0.77
lof	4	14 927 951	3 731 988	6.38**		28 096 706	7 024 177	6.64**	
Quadratic	2	119 087 901	59 543 950		0.97	121 696 714	60 848 357		0.98
lof	3	3 672 664	1 224 221	2.09NS		1 889 766	629 922	0.60NS	
Plateau−linear	2	122 107 399	61 053 700		0.99	120 445 312	60 222 656		0.97
lof	3	653 166	217 722	0.37NS		3 141 168	1 047 056	0.99NS	
Weibull	2	120 008 694	60 004 347		0.98	121 432 644	60 716 322		0.98
lof	3	2 751 871	917 290	1.57NS		2 153 836	717 945	0.68NS	

NOTE: **, significant at $P = 0.01$; NS, nonsignificant at $P = 0.05$.

[a] Linear, y = intercept + ($b \times O_3$); quadratic, y = intercept + ($b \times O_3$) + ($c \times (O_3 \times O_3)$); plateau−linear, $y = c + t \times b \times (O_3 - \theta)$; if $O_3 < \theta$, then $t = 0$, if $O_3 > \theta$, then $t = 1$; Weibull, $y = \alpha \exp[-(O_3/\sigma)^c]$. lof = ozone SS (from ANOVA on Table 3) − model SS; measures model lack of fit. F = lof MS/residual MS (from ANOVA on Table 3). R^2 = model SS/ozone SS (from ANOVA on Table 3).

TABLE 6. Predicted yield (kilograms per hectare) expressed as percent of actual measured yield for each O_3 treatment concentration as estimated by the quadratic, plateau−linear, and Weibull models for two field-corn hybrids exposed to O_3 in open-top chambers for 83 days in 1981

Model[a]	7 h/day seasonal mean O_3 concn. (ppm) 0.015	0.044	0.073	0.010	0.129	0.156
Hybrid 'Pioneer 3780'						
Quadratic	100.9	101.5	91.4	105.3	107.3	93.9
Plateau−linear	98.7	101.0	98.0	103.9	102.7	97.7
Weibull	101.4	101.4	92.7	104.4	103.5	95.1
Hybrid 'PAG 397'						
Quadratic	100.2	96.3	104.7	96.8	99.8	102.7
Plateau−linear	101.3	92.9	104.6	100.9	97.1	103.7
Weibull	102.7	93.8	103.2	98.4	101.8	101.5

[a] Quadratic: 'Pioneer 3780', $y = 10\,920 + (16\,871 \times O_3) + (-393569 \times (O_3)^2)$; 'PAG 397', $y = 11\,163 + (55\,321 \times O_3) + (-600553 \times (O_3)^2)$. Plateau−linear: 'Pioneer 3780', $y = 10\,849 + t \times (-78993 \times (O_3 - 0.071))$; 'PAG 397', $y = 11\,993 + t \times (-105751 \times (O_3 - 0.092))$. Weibull: 'Pioneer 3780', $y = 11\,159\ e^{-(O_3/0.155)^{3.071}}$; 'PAG 397', $y = 12\,151\ e^{-(O_3/0.161)^{4.594}}$.

TABLE 7. Results of split-plot analysis of variance (balanced data) and Weibull model partitioning of (ozone + hybrid) SS of field-corn data. Plants were exposed to 7-h seasonal means of 0.015, 0.044, 0.073, 0.100, 0.129, and 0.156 ppm O_3 for 83 days during 1981

Source[a]	df	Grain yield (kg/ha) SS	MS	R^2
Analysis of variance				
Blocks	2	12 584 577	6 292 289 **	
Ozone	5	239 966 869	47 993 374 **	
Blocks × ozone (error *a*)	12	11 582 233	965 186	
Hybrid	1	21 187 302	21 187 302 **	
Hybrid × ozone	5	6 380 180	1 276 036	
Residual (error *b*)	20	21 470 509	1 073 525	
Weibull model partitioning[b]				
(ozone + hybrid)	11	267 534 351	—	—
Simple	2	238 807 606	119 403 803 **	0.89
Common'−simple	1	19 792 053	19 792 053 **	0.97
Full−common	2	4 028 981	2 014 491	0.98
lof (full)	6	4 905 711	817 619	—

NOTE: **, significant at the 0.01 level of confidence.

[a] "Residual" and "blocks × ozone" are estimated using all data including nonchambered plots. All other effects are estimated using only chambered plot data. The two replications of the NF-1 treatment in each of two blocks were averaged to remove imbalance.

[b] (ozone + hybrid) = "ozone" SS + "hybrid" SS + "hybrid × ozone" SS from split-plot ANOVA of balanced design data. Simple = SS (Weibull model with 1α, 1σ, $1c$) − correction factor; requires same yield level and response to O_3 for both hybrids. Common−simple = SS (Weibull model with 2α, 1σ, $1c$) − SS (simple model); allows different yield levels for the hybrids but requires same proportional response to O_3. Full−common = SS (Weibull model with 2α, 2σ, $2c$) − SS (common model); allows each hybrid to have its own yield level and response to O_3. lof = (ozone + hybrid) SS − SS (Weibull model); measures the lack of fit. Pooled error *a* + error *b* with the summed df was used for testing (1 032 898 with 32 df). R^2 = Weibull model SS/(ozone + hybrid) SS from balanced design ANOVA.

[c] Common Weibull model parameters: $\alpha_{3780} = 10\,725$ (SE 255); $\alpha_{397} = 12\,512$ (SE 269); $\sigma = 0.160$ (SE 0.003); $c = 3.709$ (SE 0.421).

When the 7-h seasonal mean O_3 concentration exceeded about 0.07 ('Pioneer 3780') or about 0.09 ppm ('PAG 397'), the models predicted dramatic yield reductions with increasing O_3. In the only other field dose−response study with field corn, Heagle, Philbeck, and Knott (1979) exposed hybrid 'Coker 16' to four O_3 concentrations (0.02, 0.07, 0.11, and 0.15 ppm seasonal 7-h mean for 82 days) and found a significant seed yield reduction (16% total seed weight and 9% 100-seed weight) only for the 0.15 ppm O_3 treated plants. We had yield reductions of 57−62 for total seed weight and 38−40% for 100-seed weight at 0.156 ppm O_3. Weibull regression analysis of the Heagle, Philbeck, and Knott (1979) data produced loss estimates of 0.3% at 0.06 ppm and 2.9% at 0.10 ppm O_3 relative to a background of 0.025 ppm O_3 (Heck *et al.* 1983). Our common Weibull model predicted losses of 2.6 (1.2−4.7%) at 0.06 ppm O_3 and 16.3% (11.4−22.1%) at 0.10 ppm relative to 0.025 ppm O_3. This study demonstrates considerably more sensitivity to O_3 at the higher concentrations than was estimated by Heagle, Philbeck, and Knott (1979).

The choice of a model to represent the yield responses to O_3 can be very important at the lower (up to 0.10 ppm) O_3 concentrations. For example, at ambient O_3 concentrations (0.044 ppm), hybrid 'PAG 397' exhibited a slight but nonsignificant yield increase and hybrid 'Pioneer 3780' exhibited an apparent plateau effect up to 0.073 ppm when compared with the 0.015 ppm control. However, one must be careful not to overemphasize the importance of an individual concentration point when establishing the models. While there is research that suggests the existence of a threshold for foliar injury development, we know of no studies which support the existence of a strict threshold concentration for yield effects (as suggested

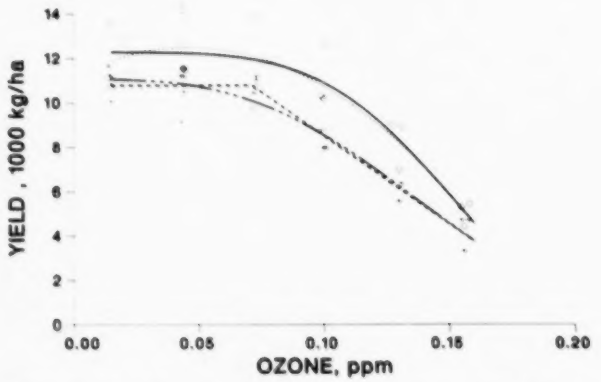

FIG. 3. Weibull, quadratic, and plateau–linear model dose–response curves for field-corn grain yield as a function of the 7-h seasonal mean O_3 concentrations (20 June – 10 September 1981). Hybrid 'PAG 397' (◇), quadratic (···), Weibull (—). Hybrid 'Pioneer 3780' (+), plateau–linear (---), Weibull (–·–·–).

by use of a plateau–linear model). Likewise, we have no evidence to suggest that the apparent yield stimulation was anything other than experimental error. Statistically, these hybrids showed no difference in response to O_3 (no hybrid × ozone interaction), and the Weibull model was only slightly inferior to the plateau–linear for one hybrid or to the quadratic for the other hybrid. The Weibull appears to be an adequate choice as a single model to describe the responses of both hybrids. The NCLAN program has adopted the use of the Weibull model for dose–response estimates because of its flexibility in fitting many different types of data sets (the curve can take different shapes) and the ability to test for homogeneous responses to a stress (Heck *et al.* 1983; Heck *et al.* 1984). Although statistically indistinguishable from the Weibull, the other models have been presented because of the slightly different estimations of O_3 effects in the ambient concentration range.

Compared with the estimates for overall seed yield (kilograms per hectare), the yield loss estimates for 100-seed weight were slightly greater at low O_3 concentrations but were less at higher O_3 concentrations (3.7 at 0.06 ppm and 14.6% at 0.10 ppm), indicating a slightly more linear response curve for seed weight. Seed number was unaffected at lower O_3 concentrations (up to 0.07–0.10 ppm) but exhibited the steepest dose–response slope at the higher O_3 concentrations and became an increasingly important factor in the overall grain yield reduction. Heagle, Philbeck, and Knott (1979) had noted a similar phenomenon. The amount of the cob that was filled with kernels was not appreciably reduced except for the highest O_3 treatment (6–7%), indicating that the overall yield effects were due primarily to reduced cob size and seed size. Cob length and width were reduced about equally. The height at which the ear developed was reduced more than total plant height, which may have decreased the amount of irradiance received by the ear leaf and thus decreased the amount of photosynthate available to fill the kernels.

The barren ear tips in the high O_3 treatments (0.156 ppm) were also often curved and twisted (especially in 'Pioneer 3780'), a symptom resembling phosphorus deficiency. The soil tests showed no field variation in the amounts of phosphorus and phosphorus deficiency symptoms were not noted in the lower concentration O_3 plots. Thus, it appeared that either O_3 induced the symptom directly or that O_3 inhibited the uptake and (or) utilization of phosphorus.

The amount of foliar injury (1–5%) noted at the higher O_3 concentrations (0.129 and 0.156) was not indicative of the dramatic decreases in yield. These two hybrids of field corn suffered large yield reductions with little foliar symptom expression. Hagle, Philbeck, and Knott (1979) had found that the magnitude of foliar injury was a poor indicator of the effects on kernel weight. This suggests that field surveys based on foliar symptom expression are probably of little value in assessing the magnitude of O_3 impacts on field corn.

In the ongoing NCLAN economic modeling effort, the effects on crop yield obtained with response models serve as a starting point for the economic analyses. The economic modeling effort will be facilitated if various data sets on the same crops can be combined into one model. The analyses in this study have shown that the O_3 responses of these two corn hybrids can be combined in one response model. However, these data cannot be combined with the 'Coker 16' data of Heagle, Philbeck, and Knott (1979) (Heck *et al.* 1983). Plants actually respond only to the O_3 which enters the tissues. Plant water status can alter stomatal aperture and thus different O_3 uptake rates may occur at similar ambient O_3 concentrations. Factors that affect plant water status (soil type, precipitation, irrigation, irradiance, air movement, etc.) may thereby also affect plant sensitivity to O_3. While we had a season with higher than normal rainfall, Heagle, Philbeck, and Knott (1979) irrigated to prevent moisture stress and thus moisture availability alone probably cannot explain the greater sensitivity in this study. The reason for the heterogeneity of responses could be any or all of several factors: different regions, different years, artificial irrigation (used by Heagle, Philbeck, and Knott 1979) vs. no irrigation, chamber fans on all night (Heagle, Philbeck, and Knott 1979) vs. off at night, or different hybrids. However, NCLAN does have information available for soybean that shows one can combine data from different regions, years, and cultivars (Heck *et al.* 1983), i.e., region, year, and cultivar may not add significant variance if the basic experimental techniques are uniform.

Although this study does indicate greater O_3 sensitivity in field corn than previously found by Heagle, Philbeck, and Knott (1979), our conclusions are similar: little or no adverse effects from the O_3 concentrations currently occurring in corn-producing regions (0.04 to 0.07 ppm for a 7-h seasonal mean). From the other studies performed at Argonne National Laboratory on other important crops in the Midwest, we have found that field corn is more sensitive than grain sorghum (Kress and Miller 1985) but less sensitive than winter wheat (Heck *et al.* 1984) and considerably less sensitive than soybean (Kress and Miller 1983). One must be cautious regarding extrapolation of these data beyond the conditions of the experiments. Future NCLAN studies will examine the effects of varying plant water status on the O_3 sensitivity of crop plants.

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